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ANALYTIC AND EXPERIMENTAL

INTERIOR BALLISTICS OF LIGHT GAS GUNS

TERMINAL BALLISTICS BRANCH
WEAPONS EFFECTS DIVISION

JANUARY 1974

FINAL REPORT: February 1971 to June 1973

AIR FORCE ARMAMENT LABORATORY

AIR FORCE SYSTEMS COMMAND ● UNITED STATES AIR FORCE

EGLIN AIR FORCE BASE, FLORIDA

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER AFATL-TR-74-32	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) SIMPLIFIED ANALYTIC AND EXPERIMENTAL INTERIOR BALLISTICS OF LIGHT GAS GUNS		5. TYPE OF REPORT & PERIOD COVERED Final Report February 1971 - June 1973
		6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) Otto K. Heiney		8. CONTRACT OR GRANT NUMBER(s)
9. PERFORMING ORGANIZATION NAME AND ADDRESS Weapons Effects Division (DLRD) Air Force Armament Laboratory Eglin Air Force Base, Florida 32542		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS Project 25490313
11. CONTROLLING OFFICE NAME AND ADDRESS Air Force Armament Laboratory Air Force Systems Command Eglin Air Force Base, Florida 32542		12. REPORT DATE January 1974
		13. NUMBER OF PAGES
14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office)		15. SECURITY CLASS. (of this report) Unclassified
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18. SUPPLEMENTARY NOTES

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19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

A two-stage light gas gun incremental interior ballistic formalism is presented, along with a FORTRAN IV computer program that utilizes the system. Typical input and output data, both plotted and tabular, are included. A standard conventional gun ballistic analytic approach is coupled to a mathematical model of the light gas chamber. Correlations of the mathematical model and computer predictions to experimental device firings are demonstrated.
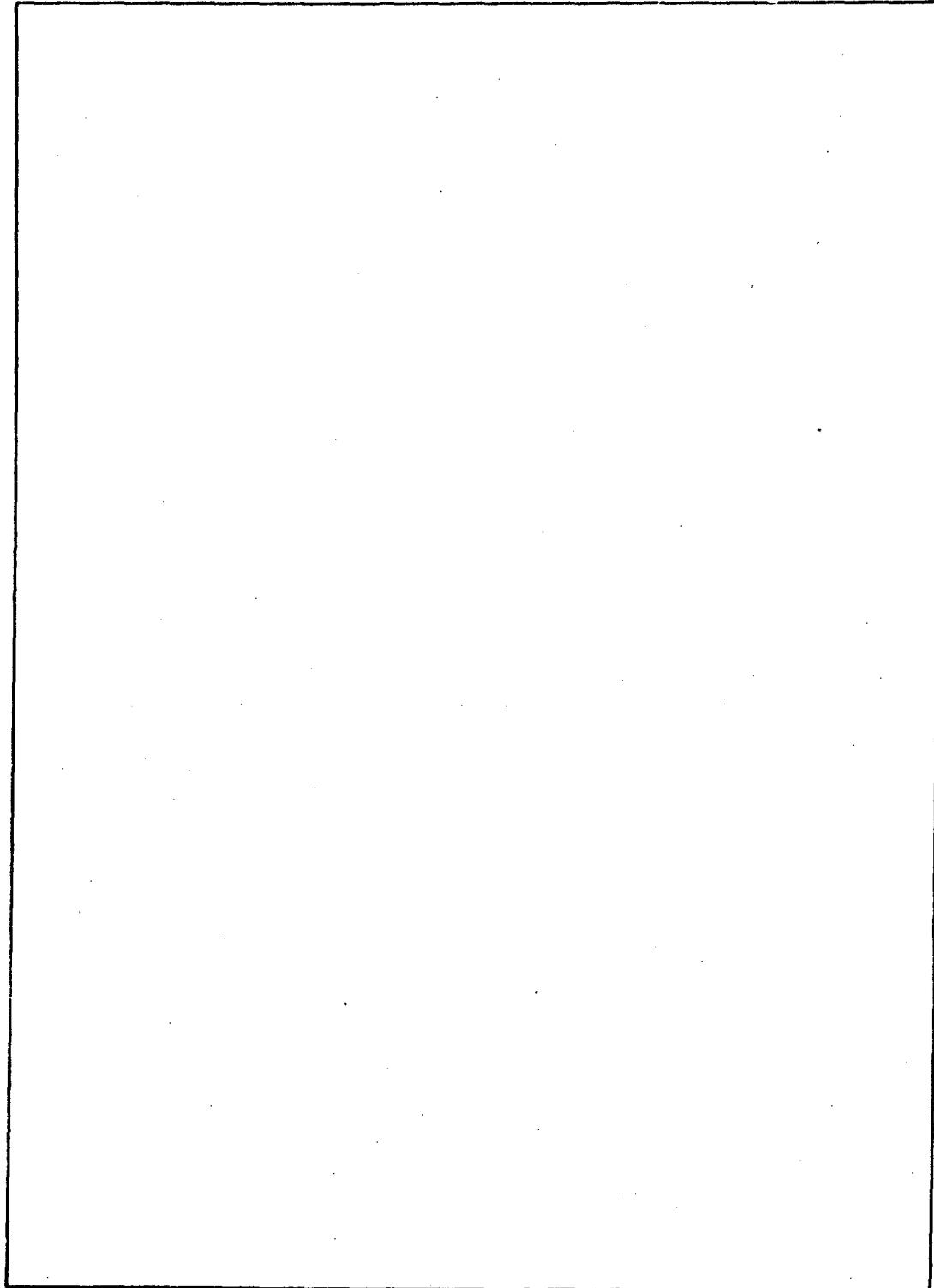
PREFACE

This report has been generated under the terminal ballistic analysis portion of Project 25490313. It is, in essence, an extension of a closed breech gun interior ballistic analysis reported in Air Force Armament Laboratory Technical Report AFATL-TR-69-42 (see Reference 1). The computer algorithm was developed by Otto K. Heiney, Captain, USAFR, as part of the duties associated with the Air Force Reserve mobilization program.

This technical report has been reviewed and is approved.
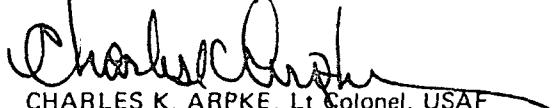
CHARLES K. ARPKE, Lt Colonel, USAF
Chief, Weapons Effects Division

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TABLE OF CONTENTS

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SECTION I

INTRODUCTION

This report presents a first order mathematical model of the interior ballistics of two-stage light gas guns. The model and experimental data are presented for a helium system, but conceptually, any driver gas can be used if the thermodynamic properties are known.

Section II describes the models of the combustion chamber, the pump tube, and the launch tube, as well as the mechanism of coupling between the chambers. The results of the analysis (Equations 11, 20, and 24) are in an incremental form specifically tailored for digital machine computation.

The computer program generated from the analysis is listed in Section III, along with samples of input and output data, as well as a test case.

Section IV illustrates the comparison of experimental to analytic data fit and discusses the particular experimental system utilized to verify the generated mathematical analysis. The analytic approach used is essentially heuristic. During this effort, engineering simplicity has been selected over mathematical elegance. The vague or undefined lumped parameter constant approach has been avoided as much as possible.

SECTION II

ANALYSIS

1. SYSTEM DESCRIPTION

The light gas system used to generate and calibrate this mathematical model is shown schematically in Figure 1. This system is a typical two-stage light gas gun which uses helium as the working fluid. The mechanism of operation is to burn gun propellant in the combustion chamber until a pressure is generated (around 900 psi) which, for this device, will shear the restraining ring on the piston and allow it to travel into and compress the helium gas on the pump tube stage. The gas being compressed eventually reaches a much higher pressure than the driver gas, due to the inertia of the relatively heavy piston traveling at a velocity of approximately 2,000 ft/sec. This pump tube gas is compressed until it reaches a pressure adequate to shear the restraining mechanism on the propelled payload. The projectile is then accelerated at high velocity down the evacuated launch tube, utilizing the very low pressure gradient decrement associated with the low molecular weight of the light gas. The simplified heuristic mathematical analysis of the physical phenomena occuring in the system is discussed in the following paragraphs. Table 1 defines the symbols used in the mathematic analysis. Figure 2 illustrates the experimental launcher system used, and Figure 3 shows the target area and target evacuation system.

2. COMBUSTION TUBE ANALYSIS

The solution for the combustion tube, or propellant burning side of the device, is through a standard gun ballistic approach similar to that given in Reference 1.

The energy balance for this section will be

$$E_1 = E_2 + E_3 + E_4 \tag{1}$$

Where

E_1 is the energy put into the system by combustion of the solid propellant.

E_2 is the translational energy of piston.

E_3 is the heat loss to walls.

E_4 is the energy required to accelerate unburned propellant and combustion gases.

The chemical energy generated will be

$$E_1 = m_N C_V (T_0' - T_c) \tag{2}$$

Reference:
1. Heiney, O. K., Analytic and Experimental Interior Ballistics of Closed Breech Guns, Air Force Armament Laboratory AFATL-TR-69-42, May 1969 (Unclassified).

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LAUNCH TUBE

LINER

HIGH PRESSURE SECTION

SABOT

PUMP TUBE

PISTON

COMBUSTION TUBE

POWDER

PRIMER

120"

12.5"

121" +

71.25"

Piston wt: 152 grams
Sabot wt: 1 gram
Powder Charge: 300 - 800 grams
Launch Tube Inside Diameter: 0.500 inch

Pump Tube Inside Diameter: 2.300 inches
Combustion Tube Inside Diameter: 4.0 inches
Pump Tube Effective Length: 135.9 inches
Combustion Tube Effective Length: -71.25 inches

Launch Tube Effective Length: -132.5 inches
Sabot Shearing Pressure: 20,000 lb/in^2
Pump Tube Outside Diameter: 4 inches
Launch Tube Outside Diameter: 2½ inches

Figure 1. Light Gas System
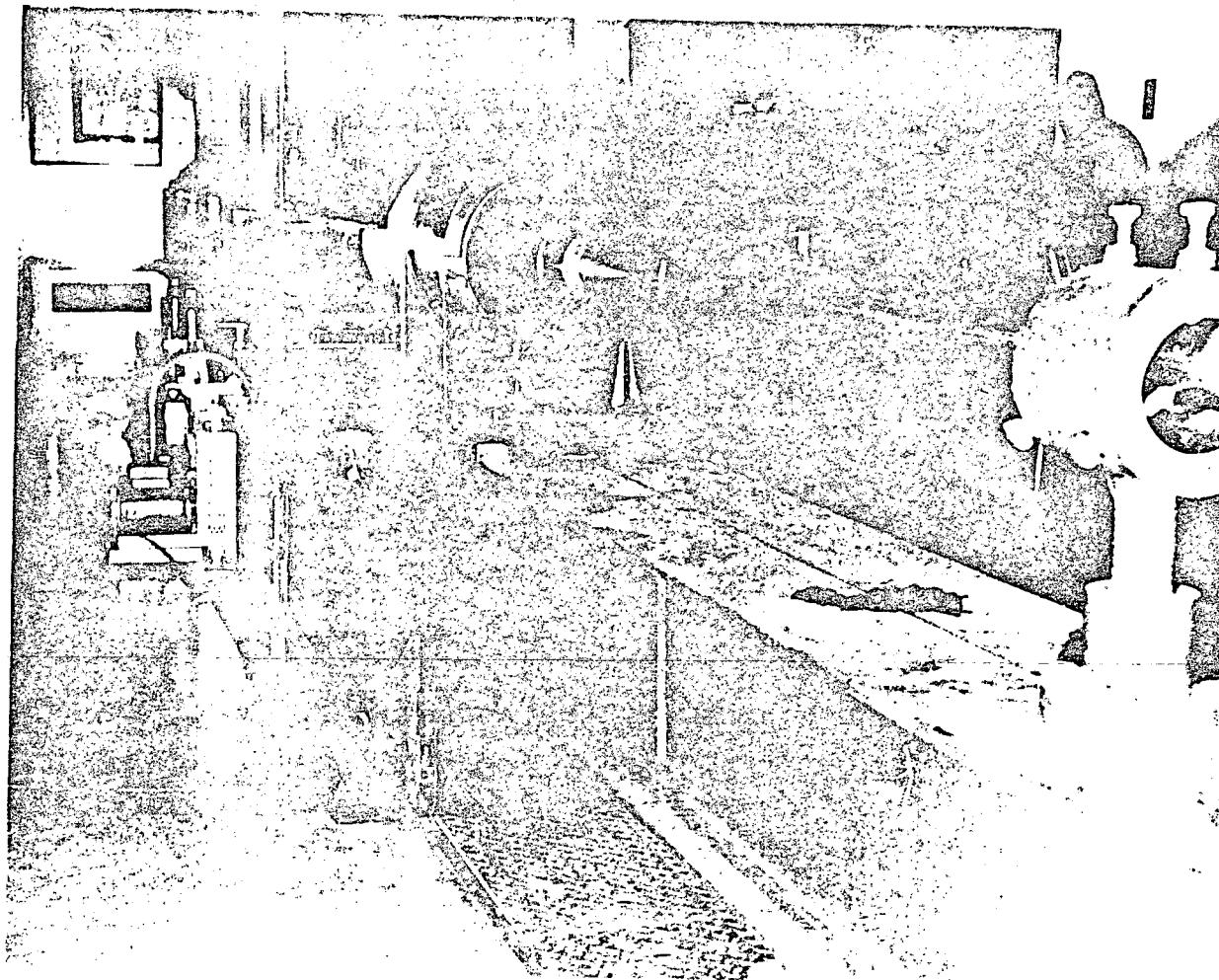
Figure 2. Experimental Launch System
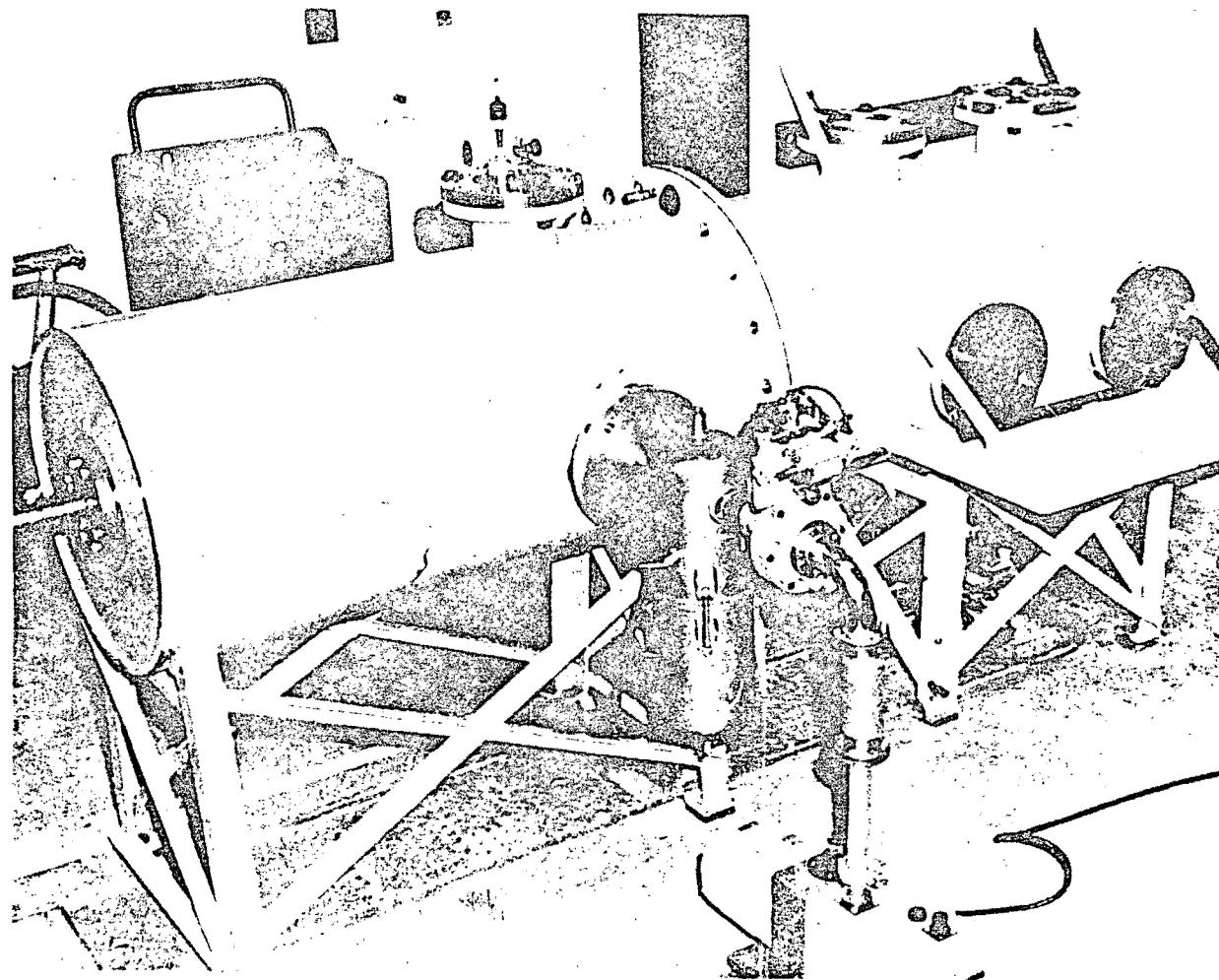
Figure 3. Target Area and Evacuation System

TABLE 1. LIST OF SYMBOLS USED FOR MATHEMATICAL ANALYSIS

A_c	Bore area of combustion chamber
a_p	Acceleration of piston
A_S	Bore area launch tube
a_S	Acceleration at payload
C_v	Specific heat of gas at constant volume
C_W	Total mass of gun propellant
F	Force
g	Acceleration value of gravity
F_B	Impetus of propellant
m_a	Pseudo-mass of compression piston
m_B	Mass of compression piston
M_N	Molecular weight of light gas
m_n	Mass of propellant burned
m_S	Mass of payload
n_L	Mass of pump tube gas charge
P_c	Pressure in combustion chamber
P_L	Pressure in pump tube chamber
P_N	Net action pressure on compression piston
P_S	Pressure at projectile base
R	Universal gas constant
r	Linear propellant burning rate
S_B	Burning surface of propellant
t	Time

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TABLE 1. CONCLUDED

T_c	Gun propellant gas temperature
T_L	Gas temperature in pump tube
T_0'	Isochoric flame temperature of propellant
V_A	Volume of pump tube chamber
v_c	Velocity of compression piston
V_P	Initial volume of propellant chamber
v_S	Payload velocity
X_c	Reference distance to compression piston
X_S	Payload distance reference
β_c	Heat loss factor combustion chamber
β_2	Heat loss factor pump tube
δ	Gun propellant gas density factor
ρ_P	Density of propellant
γ_c	Specific heat ratio of combustion gases
γ_L	Specif heat ratio of light gas

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The translational energy of payload will be

$$E_2 = \frac{1}{2} m_B v_c^2 \qquad (3)$$

The heat loss of the gases is proportional to the distance traveled, which is roughly proportional to the square of the velocity (Reference 2). This heat loss can then be approximated

$$E_3 = -\frac{1}{2} \beta_c m_a v_c^2 \qquad (4)$$

Using a Kent form solution (Reference 3) with high velocity modifications for the energy contained in the accelerating gases and unburned propellant, the following approximation can be obtained:

$$E_4 = \frac{1}{2} \frac{C_W}{g \delta} v_c^2 \qquad (5)$$

In this equation, δ equals 3 at low velocities but increases at high velocities because the density distribution becomes less uniform. This effect, and the variation of δ with payload velocity, is discussed in Reference 4.

An effective mass may be defined as

$$m_a = m_B + \frac{C_W}{g \delta} \qquad (6)$$

Then

$$E_2 + E_3 + E_4 = (1 + \beta_c) \frac{1}{2} m_a v_c^2 + P_c A_c X_c \qquad (7)$$

The term γ is defined by

$$(\gamma_c - 1) = \frac{R}{C_V} = \frac{F_B}{C_V T_0'} \qquad (8)$$

References:
2. Hirschfelder, Kershner, and Curtiss, Interior Ballistics, Volumes I and II. NDRC Reports A-142 and A-180, February and April 1943, (Declassified).
3. Kent, R. H.: "Some Special Solutions for the Motion of the Powder Gas," Physics 7, 1936.
4. Heiney, O. K.: "A New Computer-Oriented Formalism for Gun Ballistics," Proceedings 3rd ICRPG-AIAA Solid Propulsion Conference. Volume I, 3-5 June 1968 (Confidential).

Then, from Equations (2), (7), and (8)

$$m_N F_B \left(\frac{1 - T_c}{T_0} \right) = \frac{1}{2} (\gamma_c - 1) (1 + \beta_c) m_a v_c^2 \qquad (9)$$

The temperature ratio is eliminated by the introduction of the equation of state to give the basic ballistic equation for the propellant combustion chamber.

$$P_c (V_P + A_c X_c) = m_N F_B \cdot (\gamma_c - 1) (1 + \beta_c) \frac{m_a}{2} v_c^2 \qquad (10)$$

The following differential form of Equation (10) is more convenient for incremental computation:

$$\frac{dP_c}{dt} (V_P + A_c X_c) = \frac{dm_N}{dt} F_B \cdot (\gamma_c - 1) (1 + \beta_c) m_a \frac{dv_c}{dt} \frac{dX_c}{dt} \cdot P_L A_c \frac{dX_c}{dt} \qquad (11)$$

Equation (11), coupled with the expressions for propellant burning rate and those describing the motion of the projectile, provides a complete solution for the combustion chamber. The expression for gas generation is then

$$\frac{dm_N}{dt} = r S_B \rho_P \qquad (12)$$

where S_B is the total exposed propellant burning surface, ρ_P is the density of the propellant, and r is the linear burning rate of the propellant. This burning rate is a non-linear function of the combustion chamber pressure; thus, the r vs. P data must be read into the computer in tabular form.

The equation of motion for the compression piston is derived from a simple force balance:

$$P_N = P_c - P_L$$
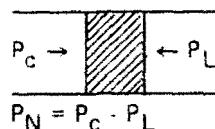
$$F = P_N A_c = m_B a_p \qquad (13)$$

$$\frac{dv_c}{dt} = a_p = \frac{A_c (P_c - P_L)}{m_B}$$

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The preceding discussion provides the solution for the pressure on the combustion side, while the following discussion develops the solution for the pump tube. The solutions are quasi independent and coupled only through piston motion.

3. PUMP TUBE ANALYSIS

The solution starts with an equation of state for this chamber:

$$P_L V_A = n_L R T_L \tag{14}$$

Then taking

$$R = C_V (\gamma_L - 1) \tag{15}$$

and differentiating gives

$$\frac{dP_L}{dt} \cdot \frac{V_A}{\gamma_L - 1} + \frac{P_L}{\gamma_L - 1} \frac{dV_A}{dt} = n_L C_V \frac{dT_L}{dt} \tag{16}$$

Equation (16) is a differential energy equation for this system. Collecting terms and including a term for the work performed by payload projectile acceleration gives

$$\frac{dP_L}{dt} = n_L \frac{R}{V_A} \frac{dT_L}{dt} - \frac{P_L}{V_A} \frac{dV_A}{dt} - (\gamma_L - 1) m_S' v_S \frac{dv_S}{dt} \tag{17}$$

Consider the last term with m_S' (handled as for the combustion on tube analysis) as a combination of the launched payload sabot and projectile weight plus a varying fraction of the compressed gas mass. The advantage of the use of helium for the working fluid is apparent here. Figure 4 gives the value of this variable (gas density gradient factor δ) as a function of projectile velocities, with n_L being the charge of helium on the light gas side.

$$m_S' = m_S + \frac{n_L}{\delta g} \tag{18}$$

After including β_2, the result for this term is

$$(\gamma_L - 1)(1 + \beta_2) m_S v_S \frac{dv_S}{dt} \tag{19}$$

This gives, finally, the basic differential pressure equation:

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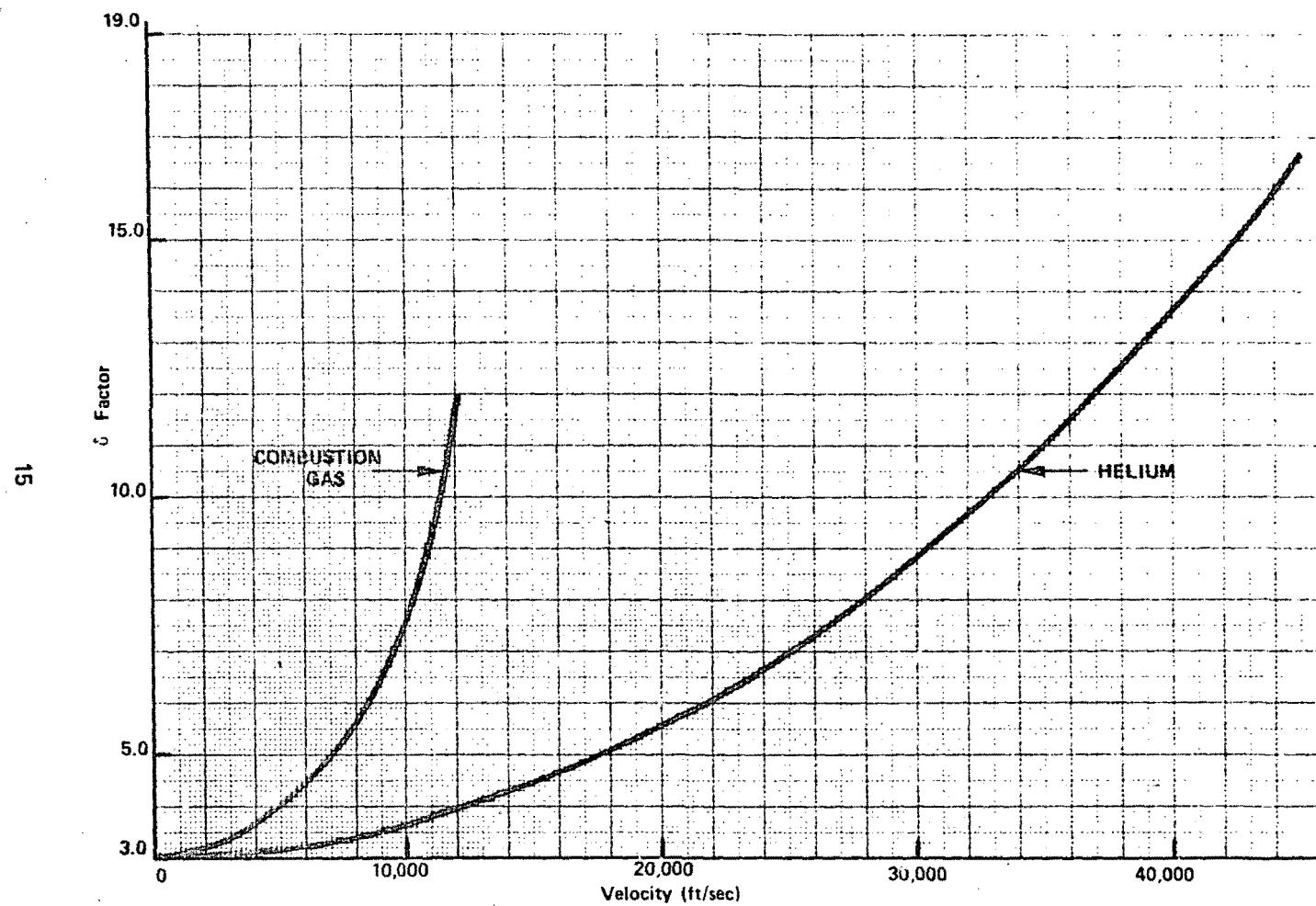
Figure 4. Gas Density Factor as a Function of Velocity

$$\frac{DP_L}{dt} = n_L \frac{R}{V_A} \frac{dt_L}{dt} + \frac{P_L A_c}{V_A} \frac{dX_c}{dt} - \frac{P_L}{V_A} A_s \frac{dX_s}{dt} - (\gamma_L - 1)(1 + \beta_2) m_S v_S \frac{dv_S}{dt}$$

(20)

The result of Equation (2) is then coupled with the results from the combustion chamber analysis. Also, required is the following relation from Reference 5 which is valid to the first order for the stepwise quasi-isentropic approach used;

$$\frac{P}{T} \frac{dT}{dt} = \frac{R}{c_p} \frac{dP}{dt}$$

(21)

Again using Equation (15) gives

$$\frac{dT_L}{dt} \cong \left(\frac{\gamma_L - 1}{\gamma_L} \right) \frac{T_L}{P_L} \frac{dP_L}{dt}$$

(22)

Equations (20) and (22) provide an incremental solution for the pump tube pressure as a function of time, when coupled with the solution for compression piston motion.

4. PRESSURE GRADIENT AND PAYLOAD MOTION

Equation (2) provides a time history of the space mean static pressure. An expression for payload motion, however, requires the pressure at the base of the shot to be defined. Reference 1 covers this pressure gradient computation in some detail. The results of that analysis provide

$$\frac{P_S}{P_L} = \left[1 + \left(\frac{\gamma_L - 1}{3} \right) \left(\frac{M_W v_S^2}{gRT_L} \right) \right]^{-\gamma_L/(\gamma_L - 1)}$$

(23)

Where P_S is pressure at the projectile and P_L is mean chamber pressure.

Equation (23) is plotted in Figure 5 and dramatically illustrates the advantage of using a low molecular weight gas as the driving medium. It is seen that at a velocity of 10,000 fps, combustion gases with a molecular weight of 24 are no longer able to deliver energy to the accelerating payload. Helium, however, with a molecular weight of 4 is seen to remain 44

Reference:
5. Liepmann, H. W., and Roshko, A.: Elements of Gas Dynamics. Wiley, 1957.

16
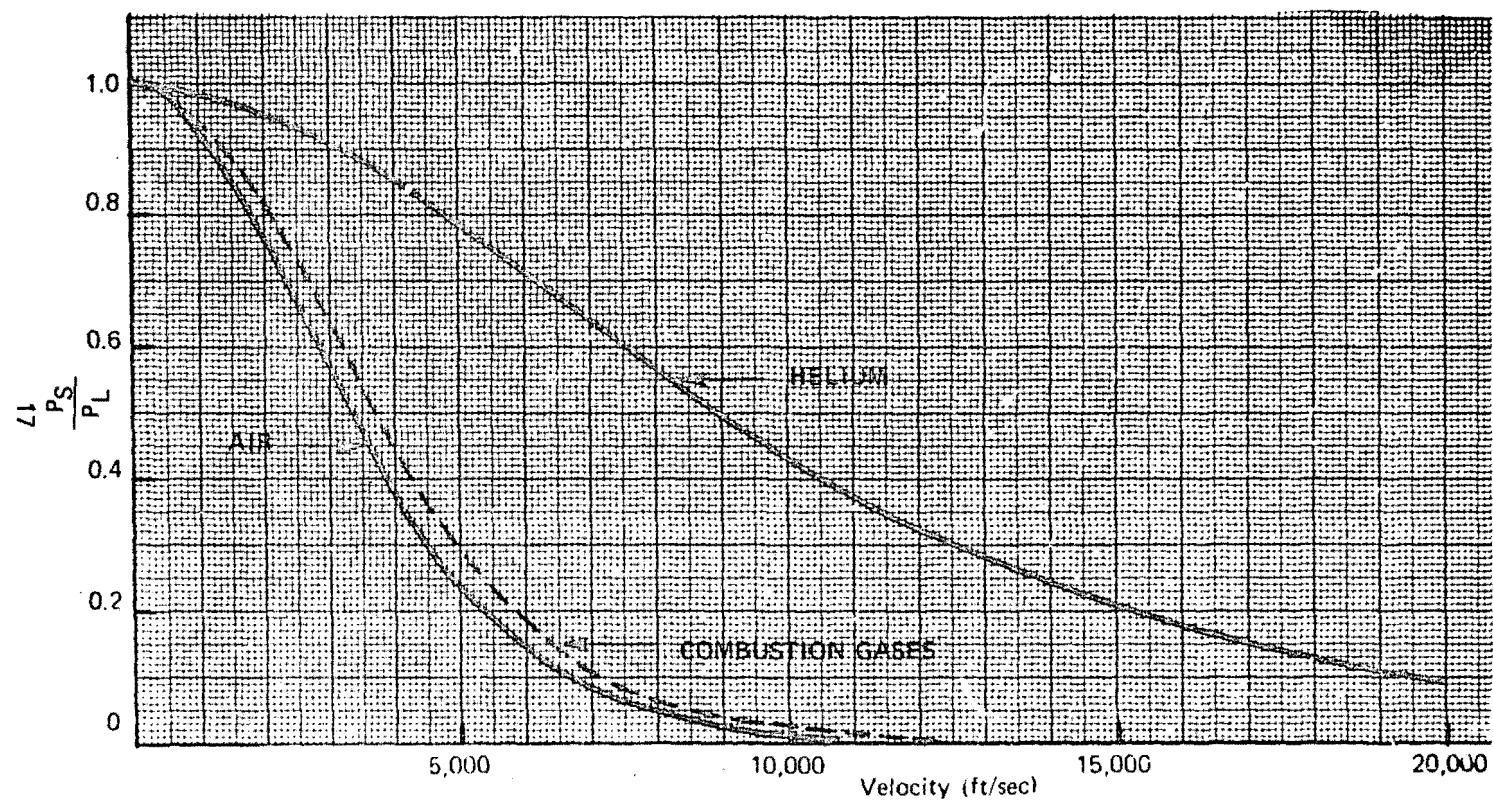
Figure 5. Pressure Gradient vs. Flow Velocity

percent efficient in it. ability to deliver useful energy to the projectile. At these velocities, regardless of the breech pressure, a gas with a heavy mean molecular weight of 24 will require virtually all the generated thermal energy to acquire the necessary directed kinetic energy to reach payload velocity. The lighter molecular weight gas will require much less of the available energy to be accelerated to payload velocity. With this pressure gradient defined, the payload motion equations become, then, quite simple in an incremental form:

$$v_S = v_S + a_S \Delta t \tag{24}$$

with

$$a_S = P_S A_S / m_S \tag{25}$$

Equations (11), (20), and (24) provide solutions for pressure in the combustion tube, pump tube, and payload motion, respectively. A complete solution is possible if the following initial conditions are known: volumes, diameters, and weights of projectiles and propellants. Additionally, initial gas pressurization and sabot release pressures must be determined accurately because the system performance is extraordinarily sensitive to these two parameters.

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SECTION III

USERS GUIDE

This section provides a nomenclature table (Table 2), a program listing, and sample input and output data so that this computer code can be run as it currently exists or it can be modified for other particular applications, such as those discussed in Reference 6.

An abbreviated flow chart is provided in Figure 6 and provides general comment statements that may be lacking in the program itself. The program may be run on reasonably small computers because core requirements are moderate. Table 3 provides a sample of the necessary case input data, and Table 4 is the associated output.

1. INPUT DATA

The input data for the program are in two main categories. The first goes in only once, and consists of 13 cards containing propellant and light gas data. The second set of data consists of case cards; three cards are required per case, and as many case cards may be stacked as is desired. The particular data are as follows:

a. Propellant and light gas data:

Card 1 contains propellant impetus, specific heat ratio, density, covolume, and type.

Cards 2 and 3 contain 20 reference pressures for propellant linear burning rates.

Cards 4 and 5 contain 20 burning rates at the fixed reference pressures.

Cards 6 and 7 contain 20 fixed propellant gas velocities.

Cards 8 and 9 contain 20 propellant gas density factors corresponding to mean density distribution in systems with the fixed propellant gas velocities.

Cards 10 and 11 contain 20 fixed helium gas velocities.

Cards 12 and 13 contain 20 system helium density distribution factors corresponding to the fixed helium gas velocities.

b. Case Cards:

Card 1 consists of the following system physical property data for the combustion chamber. Bore area, chamber volume, piston weight, piston travel, propellant web, heat loss factor, propellant charge, initial helium pressure, piston shot start pressure.

Reference:
6. Rynearson, R. J.: Optimization of a Two-Stage Light Gas Gun. Thesis, Texas A&M University, December 1972.

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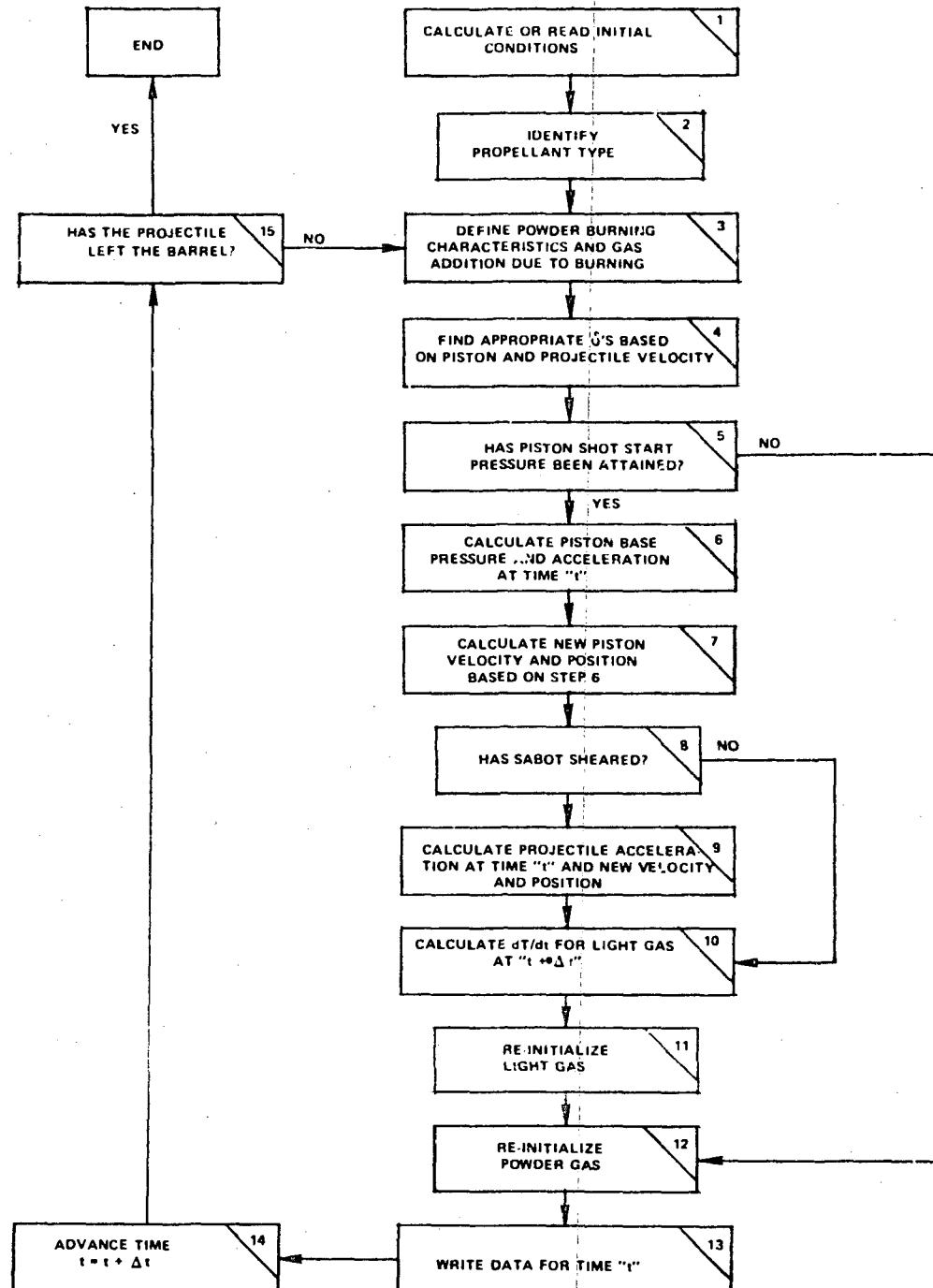
Figure 6. Code Logic Diagram

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TABLE 2. PROGRAM NOMENCLATURE

ACEL	Acceleration of the piston
ALEA	Cross-sectional area of barrel
ALGT	Acceleration of the projectile
AREA	Cross-sectional area of pump tube
BARE	Burning area of propellant
BDIS	Piston travel
BETA	Heat loss coefficient for propellant gas
BLIS	Projectile travel
BLTA	Heat loss coefficient for light gas
BP	Mass of propellant burned
CHG	Initial powder charge weight
CPEG	Projectile base pressure
CPIC	Projectile muzzle velocity
CPLG	Average light gas pressure
CPRS	Average propellant gas pressure
CVL	Covolume (η) for light gas
CVOL	Powder chamber volume
DAN	Diameter for ball type propellant
DELTA	Time increment
DFLG	"δ" factor for light gas
DIN	Propellant grain inside diameter
DLDT	Piston velocity
DOT	Propellant grain outside diameter
DPDT	Pressure slope in propellant gas

TABLE 2. CONTINUED

DPLG	Pressure slope in light gas
DTDT	Temperature slope in light gas
EFM	Effective or psuedo mass of piston
FIMP	Impetus of propellant
FPU	Fraction of propellant burned
FVOL	"Free" volume of propellant gas
GAMA	Specific heat ratio of propellant combustion gas
GIN	Initial powder gas density
GMLG	Specific heat ratio of light gas
GN	Propellant gas density
GRNS	Number of propellant grains
HCPP	Peak pressure in propellant gas
HGBL	Barrel length
HGID	Initial light gas density
HGIP	Initial light gas pressure
HGIT	Initial light gas temperature
HGIV	Initial light gas volume
HGM	Mass of light gas
HGSM	Weight of projectile
HLGP	Light gas peak pressure
IPT	Identifies propellant type
PIT	1.5, empirical correction factor
PFAC	"δ" factor for propellant gas
PLGR	Isentropic pressure ratio in light gas

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TABLE 2. CONCLUDED

PREX	Piston base pressure
PRS	Array of powder chamber pressures
PSL	δ array for light gas
PSY	δ array for propellant gas
RFST	Diaphragm burst pressure or projectile release pressure
RHO	Propellant weight density
RTF	Universal gas constant (Units = ft · $lb_f/lb_{mole}°K$) value = 2780
RUN	Pump tube length
SABPR	Powder diaphragm burst pressure or piston release pressure
SCPRS	Initial powder chamber pressure
SHOT	Piston mass
TIME	Elapsed time
TF	Flame temperature of propellant
TLGS	Average light gas temperature
TYPE	Output array to write propellant name
UBW	Unburned propellant volume
VEE	Velocity array for propellant gas
VEL1	Old piston velocity
VEL2	New piston velocity
VLE	Velocity array for light gas
VLG	Projectile velocity
VLGS	List gas volume
WEB	Propellant grain thickness
WMAL	Light gas molecular weight
WMOL	Propellant gas molecular weight
XLIN	Length of propellant grain

TABLE 3. INPUT DATA

```
346180.    1.252    .0603    29.69  M-10
   300.     500.     700.    1000.    1500.    2000.    2500.    3000.    4000.    5000.
  6000.    8000.   10000.   20000.   30000.   40000.   50000.   70000.  100000.  200000.
    .13      .2      .28      .38      .52      .68      .81      .96     1.2      1.45
   1.72     2.20     2.70     4.6      6.7      8.3      9.6     12.2     15.8     25.
     0.     500.    1000.    1500.    2000.    2500.    3000.    3500.    4000.    4500.
  5000.    5500.    6000.    6500.    7000.    7500.    8000.    8500.    9000.   12000.
   3.       3.       3.05     3.1      3.18     3.35     3.38     3.50     3.70     3.85
   4.05     4.3      4.55     4.85     5.2      5.55     5.95     6.40     7.00    12.0
     0.    2000.    4000.    6000.    8000.   10000.   12000.   14000.   16000.   18000.
 20000.   22000.   24000.   26000.   28000.   32000.   36000.   40000.   45000.   50000.
   3.       3.       3.1      3.2      3.4      3.6      3.9      4.2      4.6      5.1
   5.5      6.1      6.7      7.3      8.0      9.6     11.5     13.6     16.7     20.2
   4.15   895.      .45     136.      .018      .3      .32     100.     900.
   5000.   132.     40.      .0033   565.      300.             .196      .2
```

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TABLE 4. CASE OUTPUT

SHOT WT.   CHARGE   WEB   B.LENGTH   CHB VOL BORE AREA

2.45   9.322   2.2182   135.8   895.28   4.15

LIGHT GAS GUN DATA   SHOT WEIGHT   B.LENGTH   CHB VOL.   BORE AREA   HEAT LOSS
                      8.22338   132.27   265.22   2.195   2.28

MOLECULAR WEIGHT = 24.2   HEAT LOSS FACTOR IS 8.38   PROPELLANT USED IN SYSTEM IS M-12

PROPELLANT FORM IS SINGLE PERFORATE OR CONSTANT SURFACE

		PROPELLANT SIDE						LIGHT GAS SIDE		
TIME	CHAMB PRES	TRAVEL	PROP BURNED	PRES SLOPE	VELOCITY	GB PRES	VELOCITY	TRAVEL	BS PRES	TEMP
8.328822P	117.3	2.822	8.2116	21583.27	2.22	42.22	2.22	2.22	42.2	322.22
2.2216222	134.5	2.822	2.8231	21584.44	2.22	42.22	2.28	2.22	42.22	322.22
9.3224222	151.8	2.222	2.8347	21585.62	2.22	42.22	8.22	2.22	42.22	322.22
P.2832222	169.1	2.822	2.8462	21586.79	2.22	42.27	8.22	2.22	42.22	322.22
2.2242222	186.3	2.222	2.9578	21587.97	2.22	42.22	2.22	2.22	42.22	322.22
P.2848222	223.6	8.222	2.8693	21589.15	2.22	42.22	8.88	2.22	42.22	322.22
2.9856222	227.9	2.222	8.2809	21590.32	8.22	42.22	2.22	2.22	42.22	322.22
8.2264222	254.2	2.222	8.0924	21591.52	2.22	42.22	2.22	2.22	42.22	322.22
2.2872222	255.4	3.222	2.1848	21592.68	2.22	42.82	2.28	8.22	42.22	322.22
P.2882222	272.7	2.822	8.1156	21593.85	2.22	42.22	2.22	2.22	42.22	322.22
P.2886222	293.2	2.222	8.1271	21595.83	2.22	42.22	2.22	2.22	42.22	322.22
8.9296222	327.3	2.222	8.1387	21893.82	2.22	42.28	2.22	2.22	42.22	322.22
8.8194222	325.3	2.222	8.1527	22934.52	2.22	42.22	2.22	2.22	42.22	322.22
P.8112222	344.1	2.222	8.1633	24824.78	2.22	42.28	2.22	2.22	42.23	322.22
7.8122222	363.9	2.222	2.1755	25187.84	2.22	42.22	8.22	2.22	42.22	322.22
2.2128222	384.5	2.222	8.1983	26353.75	2.22	42.22	2.22	2.22	328.22
2.2136222	426.2	2.222	8.2248	27617.54	2.22	42.27	2.22	2.22	42.22	322.22
8.2144222	428.5	2.222	8.2228	28931.15	2.23	42.28	2.22	2.22	42.22	325.22
P.2152222	452.8	2.222	8.2353	38387.44	2.22	42.22	2.88	2.22	42.22	322.22
P.215822P	477.5	2.222	8.2525	31749.43	2.22	42.22	2.22	2.22	42.27	322.22
2.2158222	573.8	2.222	8.2699	33262.39	2.22	2.22	2.32	5.28	42.22	322.22
2.2172222	531.2	2.222	2.2883	35275.54	2.22	42.22	2.22	2.22	42.22	322.22
P.2184222	559.9	2.222	2.3876	36989.99	2.22	42.22	2.22	2.22	42.22	322.22
2.2192222	592.4	2.222	8.3288	25328.22	2.22	42.22	2.38	2.22	42.28	322.22
P.2282222	622.8	2.228	2.3495	41135.96	2.22	42.22	9.88	2.22	42.22	322.22
P.2238222	555.8	8.222	8.3721	43382.36	2.27	42.22	2.22	2.22	42.22	322.22
P.2216222	593.2	2.222	8.3968	45759.87	2.22	42.22	2.88	2.22	42.22	322.22
P.2224222	729.5	2.222	2.4211	47967.18	2.22	42.22	2.22	2.22	42.22	322.22
P.2232222	769.2	2.222	8.4474	58143.86	2.22	42.27	2.22	2.22	42.22	322.22
P.2242222	813.3	2.222	8.4749	52418.22	2.22	42.22	2.28	2.22	42.22	322.22
P.2248222	853.3	2.222	8.5836	54797.26	2.22	42.22	2.28	2.22	42.22	322.22
P.2256222	898.3	8.222	8.5336	57284.98	2.22	42.22	2.23	2.22	42.22	322.22
P.225735P	925.1	8.222	8.5425	57811.15	13.27	48.32	8.33	2.22	42.22	322.22
P.225775P	925.4	2.812	8.5442	57692.25	22.55	42.25	2.88	2.22	42.21	322.22
P.225815P	912.7	2.822	8.5456	57565.41	32.88	42.25	2.88	8.22	42.21	322.24
P.2258552	913.2	2.842	8.5471	57438.74	41.23	42.83	2.88	8.22	42.23	322.28
P.2258952	935.3	2.862	8.5487	57387.55	51.68	42.24	2.22	2.28	42.24	328.12
P.225935P	917.6	2.289	8.5583	57172.83	62.28	42.86	2.88	2.28	42.28	322.18
P.225975P	919.9	2.121	8.5518	57834.85	72.43	42.28	2.28	2.22	42.28	322.25

TABLE 4. CONTINUED

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0.0260130	922.1	0.159	0.5534	56892.96	82.88	40.11	0.00	0.00	40.11	300.33
0.0260550	924.4	0.201	0.5550	56747.88	93.36	40.14	0.00	0.00	40.14	300.42
0.0260950	926.7	0.245	0.5566	56599.17	103.87	40.17	0.00	0.02	40.17	300.52
0.0261350	928.9	0.301	0.5581	56447.18	114.40	40.21	0.00	0.02	40.21	300.63
0.0261750	931.2	0.358	0.5597	56291.59	124.96	40.25	0.00	0.02	40.25	300.76
0.0262150	933.4	0.421	0.5613	56132.68	135.54	40.30	0.00	0.02	40.30	300.89
0.0262550	935.7	0.488	0.5629	55970.36	146.15	40.35	0.00	0.02	40.35	301.04
0.0262950	937.9	0.561	0.5645	55804.67	156.78	40.40	0.00	0.02	40.40	301.20
0.0263350	940.1	0.639	0.5661	55635.63	167.43	40.46	0.00	0.02	40.46	301.37
0.0263750	942.4	0.722	0.5677	55463.25	178.12	40.52	0.00	0.02	40.52	301.55
0.0264150	944.6	0.810	0.5693	55287.55	188.82	40.58	0.00	0.02	40.58	301.74
0.0264550	946.8	0.903	0.5709	55108.56	199.55	40.65	0.00	0.02	40.65	301.95
0.0264950	949.2	1.001	0.5725	54925.31	212.32	40.72	0.00	0.02	40.72	302.16
0.0265350	951.2	1.105	0.5741	54740.80	221.26	40.80	0.00	0.02	40.80	302.39
0.0265750	953.4	1.213	0.5758	54552.09	231.88	40.88	0.00	0.02	40.88	302.53
0.0266150	955.4	1.327	0.5774	54360.18	242.70	40.96	0.00	0.02	40.96	302.48
0.0266550	957.7	1.446	0.5790	54165.11	253.55	41.05	0.00	0.02	41.05	303.14
0.0266940	959.9	1.571	0.5806	53966.90	264.42	41.15	0.00	0.02	41.15	303.42
0.0267340	962.0	1.702	0.5823	53765.59	275.31	41.24	0.00	0.02	41.24	303.71
0.0267740	964.2	1.835	0.5839	53561.21	286.25	41.34	0.00	0.02	41.34	304.01
0.0268140	966.3	1.975	0.5855	53353.78	297.18	41.45	0.00	0.02	41.45	304.32
0.0268540	968.4	2.120	0.5872	53143.35	308.12	41.56	0.00	0.02	41.56	304.54
0.0268940	970.6	2.271	0.5888	52929.94	319.10	41.67	0.00	0.02	41.67	304.98
0.0269340	972.7	2.427	0.5905	52713.58	337.10	41.79	0.00	0.02	41.79	305.32
0.0269740	974.8	2.588	0.5921	52494.32	341.12	41.92	0.00	0.02	41.92	305.69
0.0270140	976.9	2.754	0.5938	52272.18	352.16	42.04	0.00	0.02	42.04	306.06
0.0270540	979.0	2.926	0.5954	52047.22	363.23	42.18	0.00	0.02	42.18	306.44
0.0270940	981.0	3.103	0.5971	51819.45	374.31	42.31	0.00	0.02	42.31	306.84
0.0271340	983.1	3.285	0.5987	51588.93	385.41	42.45	0.00	0.02	42.45	307.25
0.0271740	985.2	3.473	0.6004	51355.69	396.53	42.58	0.00	0.02	42.62	307.68
0.0272140	987.2	3.666	0.6021	51119.76	427.68	42.75	0.00	0.02	42.75	308.12
0.0272540	989.3	3.864	0.6038	50881.21	418.84	42.91	0.00	0.02	42.91	308.37
0.0272940	991.3	4.068	0.6054	50640.05	430.02	43.07	0.00	0.02	43.07	309.03
0.0273340	993.3	4.277	0.6071	50396.34	441.22	43.23	0.00	0.02	43.23	309.51
0.0273740	995.3	4.492	0.6088	50150.13	452.43	43.41	0.00	0.02	43.41	310.00
0.0274140	997.3	4.711	0.6105	49901.45	463.67	43.58	0.00	0.02	43.58	310.50
0.0274540	999.3	4.937	0.6122	49650.34	474.92	43.76	0.00	0.02	43.76	311.02
0.0274940	1001.3	5.167	0.6138	49397.84	486.19	43.95	0.00	0.02	43.95	311.55
0.0275340	1003.3	5.403	0.6155	49114.94	497.48	44.14	0.00	0.02	44.14	312.39
0.0275740	1005.2	5.645	0.6172	48840.28	508.78	44.34	0.00	0.02	44.34	312.65
0.0276140	1007.2	5.892	0.6189	48563.88	520.11	44.54	0.00	0.02	44.54	313.23
0.0276540	1009.1	6.144	0.6206	48285.45	531.44	44.75	0.00	0.02	44.75	313.81
0.0276940	1011.0	6.402	0.6223	48005.02	542.82	44.96	0.00	0.02	44.96	314.41
0.0277340	1012.9	6.665	0.6240	47722.67	554.17	45.16	0.00	0.02	45.18	315.03
0.0277740	1014.8	6.934	0.6257	47438.43	565.55	45.41	0.00	0.02	45.41	315.66
0.0278140	1016.7	7.278	0.6274	47152.36	576.95	45.64	0.00	0.02	45.64	316.30
0.0278540	1018.6	7.488	0.6292	46864.51	588.35	45.88	0.00	0.02	45.88	316.96
0.0278940	1020.5	7.773	0.6309	46574.94	599.79	46.12	0.00	0.02	46.12	317.14
0.0279340	1022.3	8.064	0.6326	46283.71	611.24	46.37	0.00	0.02	46.37	318.33
0.0279740	1024.2	8.360	0.6343	45990.86	622.69	46.63	0.00	0.02	46.63	318.43
0.0280140	1026.0	8.662	0.6360	45596.46	634.16	46.89	0.00	0.02	46.89	319.75
0.0280540	1027.8	8.969	0.6377	45400.55	645.65	47.16	0.00	0.02	47.16	320.49
0.0280940	1029.6	9.281	0.6395	45103.20	657.15	47.44	0.00	0.02	47.44	321.24
0.0281340	1031.4	9.600	0.6412	44804.46	688.65	47.72	0.00	0.02	47.72	322.01
0.0281740	1033.2	9.923	0.6429	44504.39	680.18	48.01	0.00	0.02	48.01	322.79
0.0282140	1035.0	10.253	0.6447	44203.04	691.71	48.31	0.00	0.02	48.31	323.58
0.0282540	1036.8	10.587	0.6464	43900.48	703.25	48.61	0.00	0.02	48.61	324.41
0.0282940	1038.5	10.928	0.6481	43596.76	714.81	48.92	0.00	0.02	48.92	325.25
0.0283340	1040.2	11.274	0.6499	43291.94	726.38	49.24	0.00	0.02	49.24	326.12

TABLE 4. CONTINUED

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TABLE 4. CONTINUED

0.0330049	1170.4	91.768	0.8680	20952.13	2036.50	399.05	0.00	0.00	399.05	755.46
0.0331349	1171.2	92.747	0.8699	21331.11	2044.18	415.86	0.00	0.00	415.86	768.39
0.0331749	1172.1	93.730	0.8718	21749.47	2051.86	433.61	0.00	0.00	433.61	781.24
0.0332149	1173.0	94.717	0.8737	22210.55	2058.92	453.02	0.00	0.00	453.02	794.96
0.0332549	1173.9	95.737	0.8756	22718.07	2065.95	473.60	0.00	0.00	473.60	829.20
0.0332649	1174.8	96.720	0.8775	23276.15	2072.73	495.68	0.00	0.00	495.68	824.24
0.0333349	1175.7	97.696	0.8794	23889.45	2079.23	519.43	0.00	0.00	519.43	839.89
0.0333749	1175.7	98.696	0.8813	24563.16	2085.45	545.02	0.00	0.00	545.00	856.27
0.0334149	1177.7	99.698	0.8832	25303.13	2091.36	572.62	0.00	0.00	572.60	873.44
0.0334549	1178.7	100.724	0.8851	26115.96	2096.93	602.44	0.00	0.00	602.44	891.46
0.0334949	1179.6	101.711	0.8870	27009.11	2102.14	634.76	0.00	0.00	634.76	910.42
0.0335349	1180.9	102.722	0.8889	27991.86	2106.95	669.90	0.00	0.00	669.90	932.32
0.0335749	1182.2	103.734	0.8909	29071.43	2111.34	708.13	0.00	0.00	708.13	951.31
0.0336149	1183.2	104.748	0.8928	30251.23	2115.26	749.85	0.00	0.00	749.85	973.46
0.0336549	1184.5	105.765	0.8947	31373.06	2118.67	795.50	0.00	0.00	795.50	956.67
0.0336949	1185.8	106.782	0.8966	33021.39	2121.52	845.59	0.00	0.00	845.59	1021.58
0.0337349	1187.1	107.821	0.8985	34622.90	2123.75	900.72	0.00	0.00	900.72	1047.93
0.0337749	1188.5	108.821	0.9005	36396.93	2125.32	961.57	0.00	0.00	961.57	1075.85
0.0338149	1190.0	109.841	0.9024	38365.94	2126.13	1028.97	0.00	0.00	1028.97	1125.57
0.0338549	1191.6	110.862	0.9043	39786.61	2126.11	1103.88	0.00	0.00	1103.88	1137.27
0.0338949	1193.2	111.882	0.9062	39702.91	2125.17	1187.47	0.00	0.00	1187.47	1171.16
0.0339349	1194.8	112.922	0.9082	39823.42	2123.22	1281.18	0.00	0.00	1281.18	1207.47
0.0339749	1196.4	113.920	0.9101	39548.64	2122.05	1388.43	0.00	0.00	1388.43	1246.48
0.0342149	1197.9	114.937	0.9120	39479.14	2115.62	1505.48	0.00	0.00	1505.48	1288.52
0.0340549	1199.5	115.951	0.9140	39415.50	2109.65	1640.70	0.00	0.00	1640.70	1333.86
0.0340949	1201.1	116.962	0.9159	39356.79	2102.21	1795.28	0.00	0.00	1795.28	1383.36
0.0341349	1202.7	117.989	0.9178	39309.66	2092.41	1972.35	0.00	0.00	1972.35	1436.50
0.0341749	1204.2	118.973	0.9198	39269.32	2087.58	2177.14	0.00	0.00	2177.14	1494.82
0.0342149	1205.8	119.966	0.9217	39239.12	2066.10	2415.26	0.00	0.00	2415.26	1558.51
0.0342549	1207.4	120.953	0.9237	39220.66	2048.60	2694.08	0.00	0.00	2694.08	1628.74
0.0342949	1209.0	121.932	0.9256	39215.93	2027.58	3023.01	0.00	0.00	3023.01	1706.12
0.0343349	1210.5	122.899	0.9276	39227.35	2002.14	3414.14	0.00	0.00	3414.14	1791.87
0.0343749	1212.1	123.853	0.9295	39257.96	1971.77	3883.18	0.00	0.00	3883.18	1887.31
0.0344149	1213.7	124.791	0.9315	39311.55	1935.11	4457.63	0.00	0.00	4452.62	1994.32
0.0344499	1215.2	125.596	0.9332	39381.82	1897.62	5248.82	47.35	0.00	5248.72	2096.48
0.0344599	1215.4	125.823	0.9337	39485.30	1884.93	5239.86	144.72	0.00	5238.71	2129.75
0.0344699	1215.5	126.248	0.9342	39431.75	1872.27	5442.01	245.75	0.05	5436.51	2162.22
0.0344799	1215.9	126.272	0.9347	39460.46	1858.99	5649.59	350.60	0.09	5642.52	2195.43
0.0344899	1216.0	126.494	0.9351	39491.53	1845.28	5869.22	459.43	0.15	5856.52	2229.45
0.0344999	1217.0	126.715	0.9356	39525.08	1832.58	6098.72	572.38	0.22	6079.22	2264.25
0.0345099	1217.4	126.934	0.9361	39561.22	1815.21	6339.11	689.62	0.32	6309.88	2299.56
0.0345199	1217.8	127.152	0.9366	39600.28	1799.22	6590.62	811.32	0.42	6549.25	2336.25
0.0345299	1218.2	127.345	0.9371	39641.77	1782.42	6853.65	937.63	0.51	6797.17	2373.44
0.0345310	1218.6	127.578	0.9376	39686.42	1784.84	7126.19	1068.72	0.64	7253.60	2411.41
0.0345469	1219.0	127.789	0.9381	39734.19	1746.42	7415.81	1204.75	0.78	7318.41	2450.16
0.0345599	1219.4	127.997	0.9386	39785.19	1727.13	7715.62	1345.88	0.94	7591.43	2489.97
0.0345699	1219.8	128.243	0.9391	39839.57	1706.92	8028.31	1492.26	1.12	7872.34	2529.91
0.0345799	1220.2	128.407	0.9396	39897.49	1685.77	8354.12	1644.04	1.32	8160.75	2572.85
0.0345899	1220.6	128.628	0.9400	39959.08	1663.62	8693.11	1801.38	1.54	8456.12	2612.46
0.0346000	1221.0	128.806	0.9405	40024.51	1642.45	9045.47	1964.38	1.77	8757.76	2654.68
0.0346100	1221.4	129.022	0.9410	40093.92	1618.21	9410.88	2133.18	2.03	9064.82	2697.46
0.0346200	1221.8	129.194	0.9415	40167.47	1598.07	9789.37	2305.86	2.32	9376.32	2740.73
0.0346300	1222.2	129.383	0.9420	40245.32	1564.38	10182.53	2488.51	2.66	9691.21	2784.40
0.0346400	1222.6	129.569	0.9425	40327.61	1535.71	10583.80	2675.19	2.92	10047.53	2828.40
0.0346500	1223.0	129.752	0.9430	40414.48	1507.83	10998.44	2867.92	3.27	10324.21	2872.62
0.0346600	1223.4	129.931	0.9435	40506.08	1477.72	11423.43	3066.69	3.64	10639.17	2916.86
0.0346700	1223.8	130.107	0.9440	40602.55	1446.38	11857.48	3271.47	4.03	10959.27	2961.39
0.0346800	1224.2	130.278	0.9445	40703.99	1413.61	12299.31	3482.16	4.45	11255.13	3025.99
0.0346900	1224.6	130.446	0.9450	40810.50	1379.60	12746.07	3698.64	4.89	11551.12	3248.58

TABLE 4. CONCLUDED

0.03470PP	1225.0	130.509	0.0455	40922.19	1344.26	13198.36	3920.72	5.36	11635.36	3891.86
0.03471PP	1225.4	130.788	0.0459	41039.10	1307.68	13647.21	4140.16	5.86	12104.77	3133.83
0.03472PP	1225.9	130.923	0.0464	41161.27	1269.61	14095.55	4380.67	6.38	12356.85	3174.93
0.03473PP	1226.3	131.073	0.0469	41286.70	1230.31	14537.67	4617.89	6.94	12585.61	3214.72
0.03474PP	1226.7	131.218	0.0474	41421.37	1189.73	14970.32	4859.37	7.52	12793.51	3252.91
0.03475PP	1227.1	131.359	0.0479	41559.21	1147.91	15388.65	5104.64	8.13	12966.02	3289.23
0.03476PP	1227.5	131.494	0.0484	41702.09	1104.98	15786.32	5353.12	8.78	13118.65	3323.37
0.03477PP	1227.9	131.624	0.0489	41849.87	1060.78	16184.43	5604.19	9.45	13219.20	3355.02
0.03478PP	1228.4	131.748	0.0494	42002.32	1015.38	16512.03	5857.15	10.15	13289.30	3383.88
0.03479PP	1228.8	131.867	0.0499	42159.19	969.45	16826.02	6111.26	10.86	13318.21	3409.82
0.03480PP	1229.2	131.981	0.0504	42320.16	922.48	17101.40	6365.72	11.65	13303.57	3431.96
0.03481PP	1229.6	132.089	0.0509	42484.04	874.79	17333.65	6619.88	12.44	13243.96	3450.02
0.03482PP	1230.0	132.191	0.0514	42652.82	826.54	17518.39	6872.28	13.27	13138.43	3465.35
0.03483PP	1230.5	132.287	0.0519	42823.63	777.85	17651.83	7122.65	14.12	12986.63	3475.91
0.03484PP	1230.9	132.377	0.0524	42996.75	728.90	17738.09	7369.90	15.21	12786.07	3482.10
0.03485PP	1231.3	132.462	0.0529	43171.63	679.85	17750.07	7613.15	15.92	12546.63	3483.74
0.03486PP	1231.8	132.541	0.0533	43347.67	630.88	17712.47	7851.57	16.86	12261.50	3480.72
0.03487PP	1232.2	132.613	0.0538	43524.27	582.16	17614.00	8084.34	17.83	11936.46	3472.95
0.03488PP	1232.6	132.680	0.0543	43700.79	533.88	17455.62	8312.73	18.83	11574.70	3460.40
0.03489PP	1233.1	132.742	0.0548	43876.61	486.20	17238.50	8530.04	19.85	11184.22	3443.11
0.03490PP	1233.5	132.797	0.0553	44051.11	439.29	16964.81	8741.67	20.92	10757.39	3421.12
0.03491PP	1234.0	132.847	0.0558	44223.56	393.33	16637.56	8945.10	21.98	10318.96	3394.58
0.03492PP	1234.4	132.892	0.0563	44393.71	348.45	16260.58	9139.91	23.07	9845.05	3363.60
0.03493PP	1234.9	132.931	0.0568	44560.66	324.79	15938.33	9325.76	24.19	9348.85	3328.42
0.03494PP	1235.3	132.965	0.0573	44724.18	262.48	15375.78	9502.41	25.33	8878.95	3289.25
0.03495PP	1235.7	132.994	0.0578	44883.49	221.02	14878.19	9669.71	26.49	8386.73	3246.33
0.03496PP	1236.2	133.018	0.0583	44936.45	182.32	14351.02	9827.60	27.67	7894.49	3199.94
0.03497PP	1236.6	133.038	0.0588	45188.64	144.63	13799.71	9976.11	28.87	7406.15	3150.33
0.03498PP	1237.1	133.053	0.0593	45333.76	106.02	13229.56	10115.31	30.08	6925.16	3097.78
0.03499PP	1237.5	133.064	0.0598	45473.56	74.34	12645.92	10245.36	31.31	6454.55	3042.56
0.03500PP	1238.0	133.071	0.0603	45607.87	41.81	12053.89	10366.49	32.56	5996.84	2984.92
0.03501PP	1238.5	133.074	0.0608	45736.55	11.06	11455.38	10478.94	33.81	5554.27	2925.11
0.03502PP	1238.9	133.073	0.0613	45859.50	-17.92	10855.88	10583.00	35.28	5127.53	2863.38
0.03503PP	1239.4	133.070	0.0618	45976.07	-45.13	10262.36	10678.99	36.37	4718.44	2799.07
0.03504PP	1240.3	133.063	0.0623	46088.04	-77.57	9669.03	10767.26	37.66	4327.36	2734.34
0.03505PP	1240.8	133.053	0.0628	46193.63	-94.26	9084.31	10848.14	38.96	3954.52	2667.36
0.03506PP	1241.2	133.040	0.0633	46293.47	-116.26	8507.84	10921.98	40.27	3599.83	2598.81
0.03507PP	1241.7	133.025	0.0638	46387.61	-136.56	7944.45	10999.14	41.59	3262.84	2528.55
0.03508PP	1242.1	133.007	0.0643	46476.11	-155.18	7392.30	11049.93	42.92	2942.96	2456.47
0.03509PP	1242.6	132.988	0.0648	46559.02	-172.16	6852.86	11104.69	44.25	2639.11	2382.27
0.03510PP	1243.1	132.963	0.0653	46636.42	-187.58	6290.71	11153.72	45.59	2350.24	2305.50
0.03511PP	1243.6	132.943	0.0657	46708.36	-201.34	5753.35	11197.29	46.93	2274.12	2225.43
0.03512PP	1244.0	132.918	0.0662	46774.85	-213.52	5216.73	11235.64	48.28	1809.23	2140.93
0.03513PP	1244.6	132.892	0.0667	46835.88	-224.11	4674.25	11268.98	49.63	1552.59	2052.15
0.03514PP	1244.5	132.864	0.0672	46891.37	-233.04	4115.19	11297.44	50.99	1302.22	1949.08
0.03515PP	1245.0	132.836	0.0677	46941.16	-240.27	3552.41	11321.07	52.35	1045.89	1834.22
0.03516PP	1245.4	132.807	0.0682	46984.86	-245.53	2851.92	11330.81	53.71	779.96	1690.18
0.03517PP	1245.9	132.777	0.0687	47021.78	-248.48	2019.13	11353.32	55.07	479.20	1482.14
0.03518PP	1246.4	132.747	0.0692	47050.42	-248.03	721.52	11360.82	56.43	113.14	1050.03

CASE TERMINATED AS MAXIMUM VELOCITY REACHED AT 55.4 INCHES OF TRAVEL

LIGHT GAS PEAK PRESSURE IS 17750.0 PSI
COMBUSTION SIDE PEAK PRESSURE IS 1246.4 PSI
LIGHT GAS GUN MUZZLE VELOCITY IS 11360.8FT/SEC

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Card 2 consists of pump tube physical parameters, which are, in order: sabot start pressure, launch barrel length, initial pump tube pressure, payload weight, pump tube volume, pump tube initial temperature, launch tube area, and pump tube heat loss.

Card 3 has a propellant form flag; the number 1 indicates a constant burning surface.

2. PROGRAM OUTPUT

The program listing is given in Table 5. The output (Table 4) is for the listed input data (Table 3) and corresponds to an experimental test firing conducted with a light gas gun. The correlation of experiment to analysis for both the pump tube and the combustion tube are given in Figures 7 and 8. The time sequencing for the analytic data has been worked backward from the experimental peak pressure because, in practice, the ignition transient is exceptionally long. The phenomenally long ignition delay is due to the extremely low propellant loading density and attendant required flame spread time at low pressure. Because of the erratic combustion properties of gun propellant at very low pressure, this several hundred millisecond ignition delay is effectively non-analytic.

The computer output shows that the program will print data every 800 microseconds until the driving piston starts to move, in this case at 900 psi. The program then prints data at a rate of every 40 microseconds until the payload sabot is sheared and starts to move. This occurs at 5,000 psi light gas pressure, and the final print frequency rate becomes once every 10 microseconds.

Figures 7 and 8 present a correlation of experiment and analysis for the combustion side and for the pump side, respectively. As previously mentioned, time justification has been by coincident pressure peaking on the pump tube side.

As is seen, the correlation for both the helium and propellant chambers is very good; however, it is not exact. The pump tube side has a somewhat sharper pressure decay experimentally than is predicted by the analysis, this is doubtless due to heat loss effects or sabot friction which is not totally accounted for in the mathematical model. The combustion tube pressure rise has an analytical variance from experimental, which is to be anticipated from the non-analytic nature of the slow smouldering ignition transient described previously. Additionally, at the end of the compression stroke, the analysis predicts a slight pressure recovery , which has not been seen experimentally. The analytical muzzle velocity prediction of 11,360 ft/sec compares with the experimental velocity of 11,210 ft/sec.

In summation, it can be stated that apparently the mathematical model of the two-stage light gas system is valid for performance prediction. It serves as a useful tool in determining required propellant and gas charge loads and in optimizing sabot and piston design shot start pressures. Although useful refinements should be readily apparent, the core of the program can be easily manipulated to accept more sophisticated modeling, if required. As a heuristic design tool, the core program is largely satisfactory.

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TABLE 5. PROGRAM LISTING

```
      DIMENSION PSY(20),VEE(20)
      DIMENSION PRS(20),RATE(20),TYPE(8)
      DIMENSION PROPF (4,3)
      DIMENSION FHT(18),FHT1(4),FHT2(13) ,DATA(4)
      DIMENSION PSL(20),VLE(20)
      COMMON/    /PCPRS(1000),PBDIS(1000),RUN,PROP,NPTS
      COMMON/PLTHDR/ SHOT,CHG,WEB,CVOL,AREA,VH
      READ(4,3)FIMP,GAMA,RHO,CVL,(TYPE(N),N=1,4)
    3 FORMAT(F8.1,F8.3,F8.4,F8.2,4A2)
      READ(4,4)PRS
    4 FORMAT(10F8.1)
      READ(4,5)RATE
    5 FORMAT(10F8.3)
      READ(4,24)VEE
   24 FORMAT(10F8.1)
      READ(4,26)PSY
   26 FORMAT(10F8.3)
      READ(4,24)VLE
      READ(4,26)PSL
      PIT=1.5
      TAD=GAMA/(GAMA-1.)
    6 READ(4,7)AREA,CVOL,SHOT,RUN,WEB,BETA,CHG,SCPRS,SABPR
    7 FORMAT(F7.3,F7.3,F7.3,F7.1,F7.4,F7.2,F7.3,2F8.1)
      READ(4,14) RFST,HGBL,HGIP,HGSM,HGIV,HGIT,ALEA,BLTA
   14 FORMAT(8F10.0)
      READ(4,110) IPT,DAN,DOT,DIN,XLIN,WMOL
  110 FORMAT(I1,6F10.7)
      IF(IPT.LT.1.OR.IPT.GT.3) IPT=1
   16 NPTS=0
      EFM=0
      ACEL=0
      VEL1=0
      AVOL=CVOL
      R=0.
      RAT=0.
      NPTS=0
      KUV=0
      BLIS=0.
      HLGP=0
      HCPP=0
      ILF=1
      JFG=0
      RTF=2780.
      KUE=-1
      VLG=0.
      ALGT=0.
      TLGS=HGIT
      OTOT=0.
      GMLG=1.57
      GLG=GMLG-1.
      WMAL=4.
      DPLG=0.
      GAG=1.-(1./GMLG)
      CPLG=HGIP
      CPEG=CPLG
      TIME=0.
      DELTA=0.0001
      VLGS=HGIV
      HGID=HGIP*WMAL/(RTF*HGIT*12.)
      HGM=HGID*HGIV
      BP=0.
      VEL=0.
```

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TABLE 5. CONTINUED

```
      IF(WMOL.LE.0.0) WMOL=24.
      TF=WMOL*FIMP/RTF
      XTF=TF
      GIN=SCPRS*WMOL/(RTF*TF*12.)
      FVOL=CVOL-(CHG/RHO)
      GO TO (125,123,120,123,123),IPT
 120  FPU=0.
      RT=0.
      BARI=5.*CHG/(RHO*WEB)
      GO TO 130
 123  AOT=DOT*DOT*3.1417/4.
      AIN=DIN*DIN*3.1417/4.
      IF(IPT.EQ.4) AIN=7.0*AIN
      IF(IPT.EQ.5) AIN=19.0*AIN
      AEF=AOT-AIN
      GRNS=CHG/(AEF*XLIN*RHO)
      GO TO 130
 125  BARE=2.*CHG/(RHO*WEB)
 130  WRITE(6,8)
   8  FORMAT(1H1,61H   SHOT WT.     CHARGE        WEB    B.LENGTH    CHB VOL
     1BORE AREA//)
      WRITE(6,9)SHOT,CHG,WEB,RUN,CVOL,AREA
   9  FORMAT(F10.2,F10.3,F10.4,F10.1,F10.2,F10.2///)
      WRITE(6,29)
  29  FORMAT(24H     LIGHT GAS GUN DATA    ,60H   SHOT WEIGHT    B.LENGTH
     1CHB VOL.   BORE AREA   HEAT LOSS)
      WRITE(6,25) HGSM,HGBL,HGIV,ALEA,BLTA
  25  FORMAT(27X,F11.5,F11.2,F11.2,F12.3,F12.2)
      DATA(1)=WMOL
      DATA(2)=XLIN
      DATA(3)=DOT
      DATA(4)=DIN
      WRITE(6,30)WMOL,BETA,(TYPE(N),N=1,4)
  30  FORMAT(//21H   MOLECULAR WEIGHT = ,F5.1,23H   HEAT LOSS FACTOR IS ,
     1F5.2,32H   PROPELLANT USED IN SYSTEM IS ,4A2//)
      GO TO (31,33,35,37,61),IPT
  31  WRITE(6,32)
  32  FORMAT(58H   PROPELLANT FORM IS SINGLE PERFORATE OR CONSTANT SURFA
     1CE//)
      GO TO 60
  33  WRITE(6,34)
  34  FORMAT(47H   PROPELLANT FORM IS DETERRED SINGLE PERFORATE//)
      GO TO 60
  35  WRITE(6,36)
  36  FORMAT(35H   PROPELLANT FORM IS DETERRED BALL//)
      GO TO 60
  37  WRITE(6,38)
  38  FORMAT(47H   PROPELLANT FORM IS DETERRED SEVEN PERFORATE //)
      GO TO 50
  61  WRITE(6,62)
  62  FORMAT(49H   PROPELLANT FORM IS DETERRED NINETEEN PERFORATE//)
  60  WRITE(6,95)
  95  FORMAT(2X,11H**********,10X,18H   PROPELLANT SIDE,10X,13H*********
     1*****,5X,13H**************,10X,14HLIGHT GAS SIDE,10X,10H**********)
      WRITE(6,96)
  96  FORMAT(8X,4HTIME,4X,10HCHAMB PRES,4X,6HTRAVEL,4X,11HPROP BURNED,10
     1HPRES SLOPE,3X,17HVELOCITY**CB PRES,3X,8HVELOCITY,4X,6HTRAVEL,5X,7
     2HBS PRES,6X,4HTEMP)
      BP=0.0
      VEL2=0.
      BDIS=0.0
      PTOP=3000.
      CPRS=SCPRS
```

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TABLE 5. CONTINUED

```
      GAMB=(1.+BETA)+(GAMA-1.)
      DO 39 J=1,30,,0,1
      IF(BLIS,GE,HGBL) GO TO 39
      GO TO (74,135,74,134,134),IPT
 134  IF(RAT-WEB) 135,74,74
 135  RAT=R+.00005
      OIN=OIN+RAT
      XLIN=XLIN-RAT
      AIN=OIN=OIN+3,1417/4,
      AIX=OIN=3,1417
      IF(IPT,NE,4) GO TO 132
      AIN=7,0+AIN
      AIX=7,0+AIX
      GO TO 136
 132  IF(IPT,NE,5)GO TO 136
      AIN=19,0+AIN
      AIX=19,0+AIN
 136  AEF=AOT-AIN
      BARE=GRNS+(2.+AEF+XLIN+AIX)
 74   JA=1
      IF(CPRS,LT,300,0) GO TO 76
 78   IF(CPRS-PRS(JA))77,76,75
 75   JA=JA+1
      GO TO 78
 76   R=RATE(JA)
      GO TO 10
 77   DIT=PRS(JA)-PRS(JA-1)
      DAT=RATE(JA)-RATE(JA-1)
      PIG=CPRS-PRS(JA-1)
      DIM=((PIG/DIT)+DAT)
      R=RATE(JA-1)+DIM
 10   KG=1
      IF(VLG,LT,VLE(1)) GO TO 93
 91   IF(VLE(KG)-VLG)92,93,94
 92   KG=KG+1
      GO TO 91
 93   OFLG=PSL(KG)
      GO TO 98
 94   HIG=(VLG-VLE(KG-1))/(VLE(KG)-VLE(KG-1))
      OFLG=(PSL(KG)-PSL(KG-1))+HIG+PSL(KG-1)
 98   CONTINUE
      IF(BP-CHG) 11,80,80
 80   ONOT=0
      GO TO 12
 11   IF (IPT,NE,3) GO TO 140
      IF(RT-DAN) 145,145,150
 145  R=(R/1,5)+(1.+(,5+RT/DAN))
      RT=RT+R+DELTA
 150  IF(FPU-,9) 155,155,140
 155  BARE=BARI+(1.-(FPU+*1,7))
 140  ONOT=R+RHO+BARE
      BP=BP+(ONOT+DELTA)
      IF(HCPP,LT,CPRS) HCPP=CPRS
      IF(JFG,GT,1) GO TO 12
      IF(CPRS,_T,SABPR) GO TO 54
      DELTA=,00005
      JFG=8
 12   VEL1=VEL2
      VELY=ABS(VEL2)
      RTM=(VEL2+VEL2)/(GAMA+32,17+FIMP+PIT+TF/XTF)
      ROOT=1./(1.+(((GAMA-1.)/2,)+RTM))
      TUT=ROOT**TAD
      PREX=CPRS+TUT
```

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TABLE 5. CONTINUED

```
      KO=1
 50   IF(VEE(KO)-VEL2)51,52,53
 51   KO=KO+1
      GO TO 50
 52   PFAC=PSY(KO)
      GO TO 59
 53   HAG=(VEL2-VEE(KO-1))/(VEE(KO)-VEE(KO-1))
      PFAC=((PSY(KO)-PSY(KO-1))*HAG)+PSY(KO-1)
 59   EFM=(SHOT+(CHG/PFAC))/32.17
      PROX=PREX
      IF(VEL2.LT.0.)  PROX=CPRS
      ACEL=(PROX-CPLG)*AREA*32.17/SHOT
      VEL2=VEL1+(ACEL*DELTA)
      ACOL=(ACEL*DELTA)/2.
      BINC=(VEL1*DELTA)+(ACOL*DELTA)
      BDIS=BDIS+(BINC*12.)
 13   AVOL=CVOL+(BDIS*AREA)
      IF(ILF-3) 22,22,20
 22   IF(RFST-CPLG) 19,19,23
 19   ILF=5
 20   ALGT=CPEG*32.17*ALEA/HGSM
      VLGI=VLG
      VLG=VLG+(ALGT*DELTA)
      BLIC=(VLG*DELTA)+(ALGT*DELTA*DELTA/2.)
      BLIS=BLIS+BLIC*12.
 23   TLGS= TLGS+DTDT * DELTA
 18   OLDT=VEL2
      GLEX=-GMLG/GLG
      PLGB=1.+(GLG*VLG*VLG*WMAL/(64.3*TLGS*RTF*GMLG))
      PLGR=PLGB**GLEX
      CPEG=CPLG*PLGR
      XLGS=HGIV+(BLIS*ALEA)-(BDIS*AREA)
      VLGS=XLGS-CVL+HGM/3.
      IF(DFLG.EQ.0.) PHGM=0.
      IF(DFLG.EQ.0.) GO TO 28
      PHGM=HGM/(DFLG*32.17)
 28   CONTINUE
      PLGA=12.*CPLG*AREA*VEL2/VLGS
      EFGL=(PHGM+(HGSM/32.17))*(BLTA+1.)
      PLGB=12.*CPLG*ALEA*VLG/VLGS
      PLGC=12.*EFGL*VLG*ALGT*GLG/VLGS
      PLGD=12.*HGM*RTF*DTDT/(GLG*VLGS*WMAL)
      DPLG=PLGA-PLGB-PLGC+PLGD
      DTDT= TLGS * DPLG *GAG/CPLG
      IF(ILF-3) 54,54,56
 54   XUE=XUE+1
      IF(XUE.EQ.4) GO TO 55
      GO TO 57
 55   XUE=0
 56   CONTINUE
      KUV=KUV+1
      IF(KUV.LT.2) GO TO 57
      KUV=0
      WRITE(6,99) TIME,CPRS,BDIS,FPU,DPDT,OLDT,CPLG,VLG,BLIS,CPEG,TLGS
 99   FORMAT(F12.7,F12.1,F12.3,F12.4,7F11.2)
 57   CONTINUE
      IF(HLGP.LT.CPLG) HLGP=CPLG
      CPLG=CPLG+(DPLG*DELTA)
      OLDT=VEL2
      UBW=(CHG-BP)/RHO
      COVL=CVL*BP
      GAMV=GAMB
      IF(ACEL.LT.0.) GAMV=0.
```

TABLE 5. CONCLUDED

```
      DPDT=((DNDT*FIMP*12.)-((GAMV*EFM*ACEL*VEL2*12.)+(AREA*CPRS*VEL1*12
     1.)))/(AVOL-(UBW*COVL))
      DOPE=J
      TIME=TIME+DELTA
      FPU=BP/CHG
      IF(CPRS.GT.PTOP) PTOP=CPRS
      GN=(GIN*FVOL+BP) / (AVOL-(UBW*COVL))
      TF=CPRS*WMOL/(GN*RTF*12.)
      CPRS=CPRS+(DPDT*DELTA)
      IF(CPLG.GE.0.) GO TO 39
      HGBL=BLIS
      WRITE(6,41) BLIS
   41 FORMAT(//47H CASE TERMINATED AS MAXIMUM VELOCITY REACHED AT,F6.1,
     117H INCHES OF TRAVEL///)
   39 CONTINUE
   79 CONTINUE
      CNIT=(BLIS-HGBL)/HGBL
      CPIC=(VLG-VLGI)*CNIT+VLG
      WRITE(6,111) CPIC
  111 FORMAT(///10X,33H LIGHT GAS GUN MUZZLE VELOCITY IS,F8.1,6HFT/SEC)
      WRITE(6,112) HLGP
  112 FORMAT(10X,26HLIGHT GAS PEAK PRESSURE IS,F8.1,4H PSI)
      WRITE(6,113) HCPP
  113 FORMAT(10X,32HCOMBUSTION SIDE PEAK PRESSURE IS,F8.1,4H PSI)
      GO TO 6
      END
```

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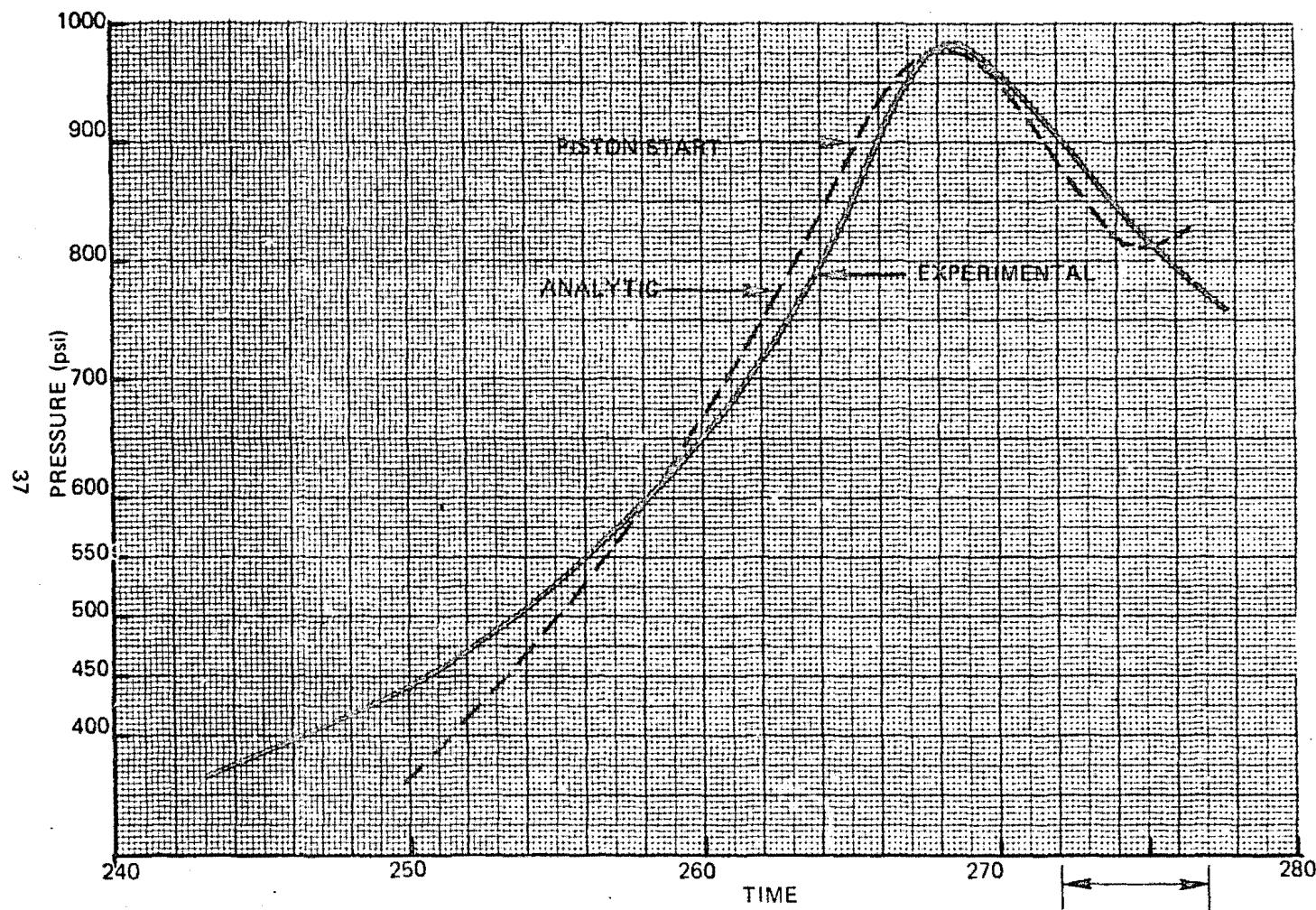
Figure 7. Combustion Tube Pressure - Firing No. 4
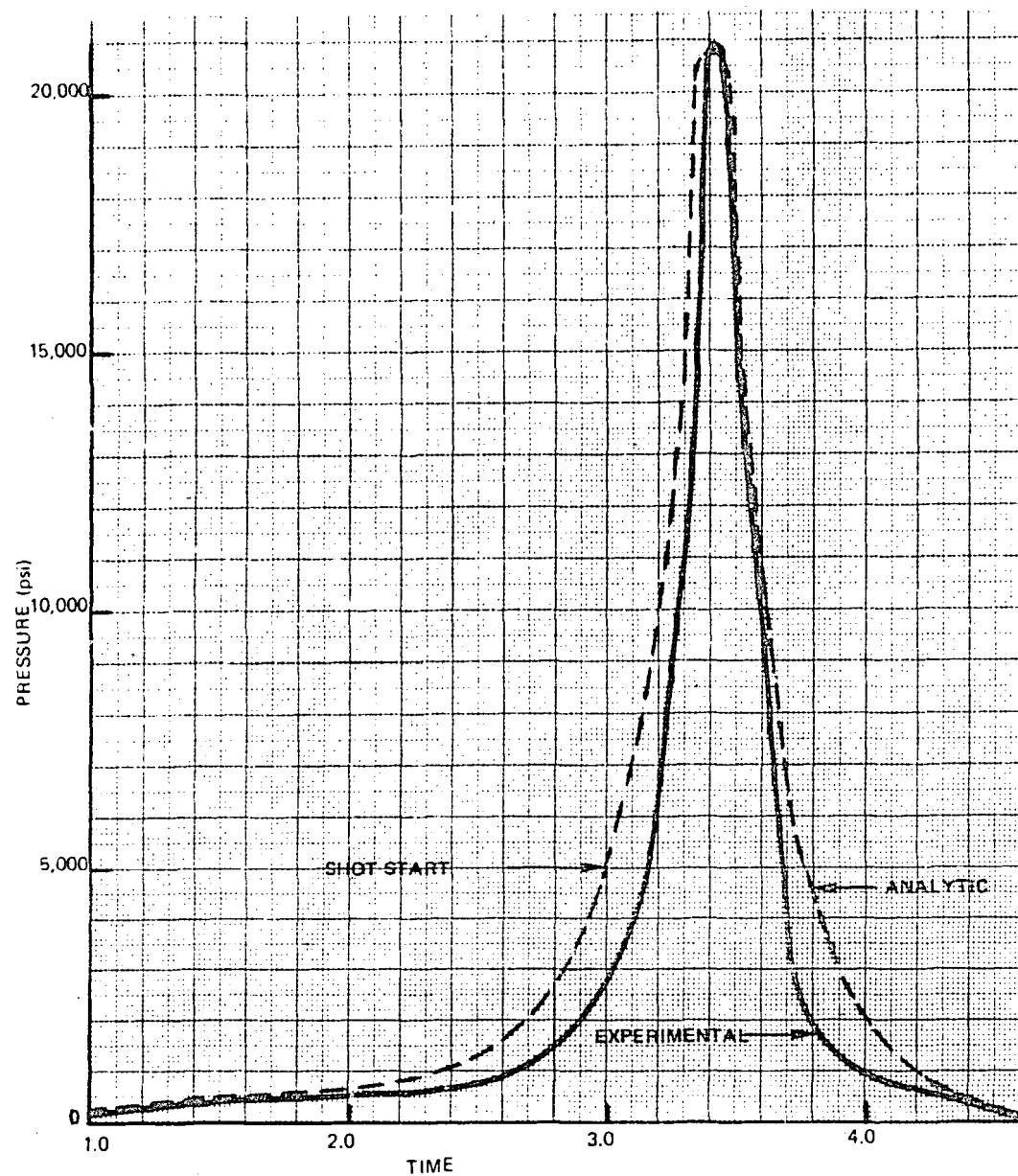
Figure 8. Pump Tube Pressure - Firing No. 4

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USN ORD LAB (CODE 730)	2
NAV ORD STN, TECH LIB	1
NAV SYS CEN, NEWPRT LAB	1
USNWC (CODE 753)	2
USNWC (CODE 4585)	1
USN WPNS EVAL FAC CODE WE	1
57 FTR WPN WG (FWOA)	1
OFF CH NAV OPNS	1
USN RSCH LAB CODE 2027	1
LOS ALAMOS SCI LAB	1
BATTELLE MEM INST	1
INST FOR DEF ANALYSES	1
SANDIA CORP	2
RAND CORP	1
USAFTFWC (CRDC)	1
HARRY DIAMOND LAB	1
DDC	2
TAWC-AY	1
DL	1
DLB	1
DLOSL	2
DLY	2
DLR	1
WE	1
ASD (YFM)	10
DLDG	10
DLDL	30
TRADOC/ADTC/DO	1

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